



09-27-04

IFC

Express Mail Label No. EV 533 735 374 US

## IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of:

Jones *et al.*

Serial No. 10/825,354

Filed: April 14, 2004

For: *System and Method for Monitoring the  
Performance of an Inert Gas  
Distribution System*

Confirmation No. 8633

Group Art Unit: 3753

Examiner: To be assigned

Attorney Docket No. 060950-5000-US

**PETITION TO MAKE SPECIAL UNDER 37 C.F.R. §1.102**Assistant Commissioner for Patents  
Washington, D.C. 20231

Sir:

Applicants, Shaw Aero Devices, respectfully petition to make special the prosecution of the captioned application.

**A. ELECTION**

Applicant submits that all claims are directed to a single invention. However, if the Office determines that all the claims presented are not obviously directed to a single invention, Applicant will make an election without traverse.

**B. SEARCH**

Applicant states that a pre-examination search was made by a professional searcher who searched the following classes and subclasses:

**CLASS**73  
137  
220  
244**SUBCLASS**23.2, 866.5  
209  
88.3  
135R

09/27/2004 SDENB081 00000042 500310 10825354

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In addition to a complete search of the above subclasses, Primary Examiner Gerald Michalsky of Group 3700 was consulted. Examiner Michalsky confirmed the searcher's opinion that the most pertinent search areas were covered by the above subclasses.

Moreover, a keyword search was also performed on the USPTO's EAST database system and the DELPHION database (including Granted European Patents, European Patent Applications, Granted German Patents, German Patent Applications, Japanese abstracts, WIPO PCT Publications, and INPADOC) utilizing a combination of the following key terms: oxygen, sensor, detector, nitrogen, analyzer, sensing, probe, fuel tank, ullage and inert.

The following patents or patent applications were located during the search:

NUMBER	INVENTOR(S)
2004/0000353	Jones
2004/0035461	Susko
6,634,598	Susko
6,698,692	Tichenor <i>et al.</i>
6,558,823	Pinney
3,691,730	Hickey <i>et al.</i>
6,547,188	Schmutz <i>et al.</i>
6,604,558	Sauer
6,012,533	Cramer
GB2374007A	Spring

The following publication was also located during the search:

*Shin-Juh Chen and Joel A. Silver*, Detection of Explosive Mixtures in the Ullage of Aircraft Fuel Tanks, 42<sup>nd</sup> AIAA Aerospace Sciences Meeting and Exhibit, 5-8 January 2004.

Copies of the above patent applications, patents, and publication are enclosed herewith, and listed on the accompanying Information Disclosure Statement.

#### C. MOST CLOSELY RELATED REFERENCES

The references that the applicants believe to be the most closely related to the claimed subject matter are discussed below. Moreover, the claimed subject matter is distinguishable over the following references for the reasons set forth below.

U.S. Patent Publication No. 2004/0035 (Jones)

This reference is owned by the Assignee of the present application. Jones describes a modular, on-board, inert gas generating system having an oxygen sensor (32) disposed along a path between the air separation module (ASM) (18) and the fuel tank ullage. In use, the oxygen sensor measures the oxygen present in the Nitrogen Enriched Air (NEA) exiting the ASM. (See paragraph [0020]). In other words, the oxygen sensor does not measure the partial pressure of oxygen present in gas removed from a space that is configured to receive the inert gas, as required by the independent claims of the present invention. Moreover, Jones does not teach a filter disposed between the aforementioned space and the oxygen sensor, as required by independent claim 1, or an indicator and a controller, as required by independent claim 15. Still further, Jones does not teach supplying an indication when the percentage of oxygen exceeds a predetermined level, as required by independent claim 32, or alarm procedures for supplying an indication when the percentage of oxygen exceeds a predetermined level, as required by independent claim 42. Accordingly, Jones cannot disclose, teach, or suggest the present invention, as claimed.

U.S. Patent No. US 6,634,598 and U.S. Patent Publication No. US 2004/0035461 (Susko)

These references describe an inerting system that includes an oxygen probe (51) that extends through a constant temperature receptacle (59) into the fuel tank (11) to monitor the oxygen partial pressure of the vapors in the tank. In other words, the oxygen sensor disclosed by Susko is placed within the fuel tank. However, as standard oxygen probes operate at elevated temperatures, which is extremely unsafe for operation within a fuel tank, Susko relies on a complicated oxygen probe (51) that is contained within a temperature controlled receptacle (59). Accordingly, Susko does not disclose an oxygen sensor that measures the partial pressure of oxygen present in gas that has been removed from a space to a safe location for measurement, as required by the independent claims of the present invention. This allows for the use of standard oxygen sensors.

Moreover, Susko does not teach a filter disposed between the aforementioned space and the oxygen probe, as required by independent claim 1. Still further, Susko does not teach supplying an indication when the percentage of oxygen exceeds a predetermined level, as required by independent claim 32, or alarm procedures for supplying an indication when the

percentage of oxygen exceeds a predetermined level, as required by independent claim 42.  
Accordingly, Jones cannot disclose, teach, or suggest the present invention, as claimed.

D. CONCLUSION

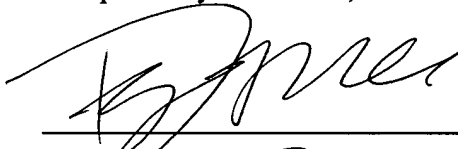
For at least the reasons set forth above, the claims, as amended, are patentable over the above references. Therefore, it is respectfully submitted that the claims are in condition for allowance.

Please charge the fee of \$130.00 (37 C.F.R. 1.17(h)) and any additional fees to Morgan, Lewis & Bockius LLP, Deposit Account No. 50-0310 (order no. 60950-5000-US).

Respectfully submitted,

Date September 24, 2004

45,645

  
Dion M. Bregman

Reg. No.

**MORGAN LEWIS & BOCKIUS LLP**

2 Palo Alto Square

3000 El Camino Real

Palo Alto, CA 94306

(650) 843-4000



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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Application of: Jones et al. Confirmation No.: 8633  
Serial No.: 10/825,354 Art Unit: 3753  
Filed: April 14, 2004 Examiner: To be assigned  
For: *System and Method for Monitoring  
the Performance of an Inert Gas  
Distribution System* Attorney Docket No.: 060950-5000-US

INFORMATION DISCLOSURE STATEMENT

Commissioner for Patents  
P.O. Box 1450  
Alexandria, VA 22313-1450

Sir:

In accordance with the duty of disclosure provisions of 37 C.F.R. §1.56, there is hereby provided certain information which the Examiner may consider material to the examination of the subject U.S. patent application. It is requested that the Examiner make this information of record if it is deemed material to the examination of the application.

1. Enclosures accompanying this Information Disclosure Statement are:
  - 1a. ☒ A list of all patents, publications, applications, or other information submitted for consideration by the office.
  - 1b. A legible copy of:
    - ☐ Each U.S. patent application publication and U.S. and foreign patent;
    - ☒ Each publication or that portion which caused it to be listed on the PTO-1449;
    - ☐ For each cited pending U.S. application, the application specification including the claims, and any drawing of the application, or portion of the application which caused it to be listed on the PTO-1449 including any claims directed to that portion;
    - ☒ all other information or portion which caused it to be listed on the PTO-1449.
  - 1c. ☐ An English language copy of search report(s) from a counterpart foreign application or PCT International Search Report.
  - 1d. ☐ Explanations of relevancy (ATTACHMENT 1(d), hereto) or English language abstracts of the non-English language publications.
2. ☒ This Information Disclosure Statement is filed under 37 C.F.R. §1.97(b):
  - ☐ Within three months of the filing date of a national application other than a continued prosecution application under §1.53(d);

- ☐ Within three months of the date of entry of the national stage as set forth in §1.491 in an international application;
- ☒ Before the mailing of the first Office action on the merits;
- ☐ Before the mailing of a first Office action after the filing of a request for continued examination under §1.114.

3. ☐ This Information Disclosure Statement is filed under 37 C.F.R. §1.97(c) after the period specified in 37 C.F.R. §1.97(b), but before the mailing date of any of a final action under 37 C.F.R. §1.113, a notice of allowance under 37 C.F.R. §1.311 or an action that otherwise closes prosecution in the application.

*(Check either Item 3a or 3b)*

- 3a. ☐ The Certification Statement in Item 5 below is applicable. Accordingly, no fee is required.
- 3b. ☐ The \$180.00 fee set forth in 37 C.F.R. §1.17(p) in accordance with 37 C.F.R. §1.97(c) is:  
☐ enclosed  
☐ to be charged to Morgan, Lewis & Bockius LLP Deposit Account No. 50-0310 (order no.           ).

*(Item 3b to be checked if any reference known for more than 3 months)*

4. ☐ This Information Disclosure Statement is filed under 37 C.F.R. §1.97(d) after the period specified in 37 C.F.R. §1.97(c), but on or before the date of payment of the issue fee.

*(Check either Item 4a or 4b)*

- 4a. ☐ The Certification Statement in Item 5 below is applicable.
- 4b. ☐ The \$180.00 fee set forth in 37 C.F.R. §1.17(p) is:  
☐ enclosed.  
☐ to be charged to Morgan, Lewis & Bockius LLP Deposit Account No. 50-0310 (order no.           ).

5. ☐ Certification Statement (applicable if Item 3a or Item 4a is checked)

*(Check either Item 5a, 5b or 5c)*

- 5a. ☐ In accordance with 37 C.F.R. §1.97(e)(1), it is certified that each item of information contained in this Information Disclosure Statement was first cited in a communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of this Information Disclosure Statement.
- 5b. ☐ Each item of information contained in this information disclosure statement was cited in a communication from a foreign patent office in a counterpart application, and the communication was not received by any individual designated in 37 C.F.R. §1.56(c) more than thirty days prior to the filing of this information disclosure statement.
- 5c. ☐ Pursuant to 37 C.F.R. §1.704(d), each item of information contained in this information disclosure statement was cited in a communication from a foreign

patent office in a counterpart application, and the communication was not received by any individual designated in 37 C.F.R. §1.56(c) more than thirty days prior to the filing of this information disclosure statement.

6. ☒ Copies of each cited U.S. patent and each U.S. patent application publication are not enclosed pursuant to the USPTO OG Notice dated 05 August 2003 waiving the requirement under 37 C.F.R. 1.98(a)(2)(i) for U.S. patent applications filed after June 30, 2003.

7. ☐ This application is a continuation application under 37 C.F.R. §1.53(b) or (d).

*(Check appropriate Items 7a, 7b and/or 7c)*

- 7a. ☐ A Petition to Withdraw from issue under 37 C.F.R. §1.313(b)(5) is concurrently filed herewith.

- 7b. ☐ Copies of publications listed on Form PTO-1449 from prior application Serial No. \_\_\_\_\_, filed on \_\_\_\_\_, of which this application claims priority under 35 U.S.C. §120, are not being submitted pursuant to 37 C.F.R. §1.98(d).

- 7c. ☐ Copies of the publications listed on Form PTO-1449 were not previously cited in prior application Serial No. \_\_\_\_\_, filed on \_\_\_\_\_, and are provided herewith.

8. ☐ This is a Supplemental Information Disclosure Statement. (Check Item 8a)

- 8a. ☐ This Supplemental Information Disclosure Statement under 37 C.F.R. §1.97(f) supplements the Information Disclosure Statement filed on \_\_\_\_\_. A bona fide attempt was made to comply with 37 C.F.R. §1.98, but inadvertent omissions were made. These omissions have been corrected herein. Accordingly, additional time is requested so that this Supplemental Information Disclosure Statement can be considered as if properly filed on \_\_\_\_\_.

9. ☐ In accordance with 37 C.F.R. §1.98, a concise explanation of what is presently understood to be the relevance of each non-English language publication is:

*( Check Item 9a, 9b, or 9c)*

- 9a. ☐ satisfied because all non-English language publications were cited on the enclosed English language copy of the PCT International Search Report or the search report from a counterpart foreign application indicating the degree of relevance found by the foreign office.

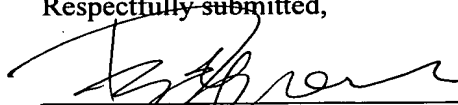
- 9b. ☐ set forth in the application.

- 9c. ☐ enclosed as an attachment hereto.

10. ☒ The Commissioner is authorized to charge any additional fee required or credit any overpayment for this Information Disclosure Statement and/or Petition to Morgan, Lewis & Bockius LLP Deposit Account No. 50-0310 (order no. 060950-5000-US).
11. ☒ No admission is made that the information cited in this Statement is, or is considered to be, material to patentability nor a representation that a search has been made (other than a search report of a foreign counterpart application or PCT International Search Report if submitted herewith). 37 C.F.R. §§1.97(g) and (h).

Respectfully submitted,

Date: September 24, 2004




45,645

Dion M. Bregman  
MORGAN, LEWIS & BOCKIUS LLP  
2 Palo Alto Square  
3000 El Camino Real, Suite 700  
Palo Alto, CA 94306  
(650) 843-4000

(Reg. No.)



<b>INFORMATION DISCLOSURE CITATION</b>  PTO-1449				<i>Complete If Known</i>	
				Application Number	10/825,354
				Filing Date	April 14, 2004
				First Named Inventor	Philip E. Jones
				Art Unit	3753
				Examiner Name	To be assigned
				Attorney Docket Number	060950-5000-US
Sheet	1	of	1		

U.S. PATENT DOCUMENTS							
Examiner Initials	Cite No.	Document Number Number - Kind Code <sup>1</sup>	Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document	Class	Subclass	Filing Date if Appropriate
		2004/0000353	01/01/2004	Jones			
		2004/0035461	02/25/2004	Susko			
		6,698,692	03/02/2004	Tichenor et al.			
		6,634,598	10/21/2003	Susko			
		6,604,558	08/12/2003	Sauer			
		6,558,823	05/06/2003	Pinney			
		6,547,188	04/15/2003	Schmultz et al.			
		6,012,533	01/11/2000	Cramer			
		3,691,730	09/19/1972	Hickey et al.			

FOREIGN PATENT DOCUMENTS								
Examiner Initials	Cite No.	Foreign Patent Document	Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document	Class	Subclass	Translation	
		Country Code <sup>2</sup> - Number <sup>3</sup> - Kind Code <sup>4</sup> (if known)					Yes	No
		GB2374007A	09/10/2002	Kidde Plc.			x	

OTHER NON PATENT LITERATURE DOCUMENTS		
Examiner Initials	Cite No.	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published
		Shin-Juh Chen and Joe A., Silver, "Detection of Explosive Mixtures in the Ullage of Aircraft Fuel Tanks", 42nd AIAA Aerospace Sciences Meeting and Exhibit, 5-8 January 2004.

Examiner Signature	1-PA/3518408.1	Date Considered	
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\*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

<sup>1</sup> See Kind Codes of USPTO Patent Documents at [www.uspto.gov](http://www.uspto.gov) or MPEP 901.04. <sup>2</sup> Enter Office that issued the document, by the two-letter code (WIPO Standard ST.3). <sup>3</sup> For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document. <sup>4</sup> Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST. 16 if possible. <sup>5</sup> Applicant is to place a check mark here if English language Translation is attached.

Burden Hour Statement: This form is estimated to take 2.0 hours to complete. Time will vary depending upon the needs of the individual case. Any comments on the amount of time you are required to complete this form should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, Washington, DC 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Assistant Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.

# (12) UK Patent Application (19) GB (11) 2 374 007 (13) A

(43) Date of A Publication 09.10.2002

(21) Application No 0108512.5

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(71) Applicant(s)

**Kidde Plc**  
(Incorporated in the United Kingdom)  
Mathisen Way, Colnbrook, SLOUGH, Berkshire,  
SL3 OHB, United Kingdom

(72) Inventor(s)

**David John Spring**

(74) Agent and/or Address for Service

**Mathisen Macara & Co**  
The Coach House, 6-8 Swakeleys Road, Ickenham,  
UXBRIDGE, Middlesex, UB10 8BZ, United Kingdom

(51) INT CL<sup>7</sup>

A62C 35/02 3/08 5/00 , B64D 37/32

(52) UK CL (Edition T )

A5A A6

(56) Documents Cited

GB 1395691 A EP 0867367 A2  
WPI Abstract Accession No: 1988-146019 &  
SU 1347940

(58) Field of Search

UK CL (Edition S ) A5A A20X4 A6  
INT CL<sup>7</sup> A62C 3/06 3/07 3/08 35/02 39/00 , B64D  
37/32  
ONLINE: WPI EPODOC JAPIO

(54) Abstract Title

**Fire / explosion protection system and method, using inert gas produced in low temperature catalytic oxidation of organic fuel**

(57) A fire / explosion protection system comprises a low temperature catalytic, inert gas producing means 18, operative to turn an organic fuel, possibly initially mixed with air or oxygen, into an inert gas, and output means B to output the inert gas into a region to be protected. Also disclosed is a method fire / explosion protection, using the aforementioned system, comprising the steps of mixing air from an air source A with organic fuel from an organic fuel source 12, for example in a mixing chamber 16, passing the mixture over a catalyst 18 for a low temperature oxidation reaction to produce an inert gas, the passing the gas into the region to be protected. The catalyst 18, which may be contained in a catalyst bed, may be heated, and be made of a noble metal such as platinum, palladium, a mix of the two, or any substance from group 7 of the periodic table. The fuel may be a hydrocarbon, oxygenated organic material, methanol and / or ethanol. The inert gas may be around 11.5 vol.% CO<sub>2</sub>, 65.4 vol.% N<sub>2</sub>, 23.1 vol.% H<sub>2</sub>O. The system may feature sensors 22 and a control unit 24 to regulate the through-flow. The system may output inert gas into an enclosed space such as the ullage space in the fuel tank of an aircraft, or of a aircraft cargo compartment.

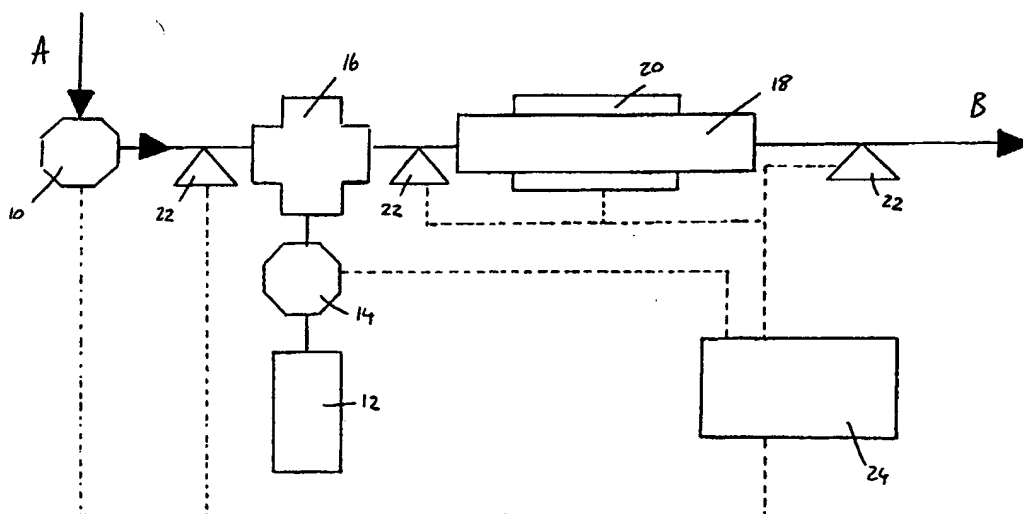


FIG. 1

GB 2 374 007

(19) World Intellectual Property Organization  
International Bureau(43) International Publication Date  
17 October 2002 (17.10.2002)

PCT

(10) International Publication Number  
WO 02/081032 A1(51) International Patent Classification<sup>7</sup>: A62C 39/00,  
A62D 1/06, A62C 3/06

(21) International Application Number: PCT/GB02/01531

(22) International Filing Date: 2 April 2002 (02.04.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
0108512.5 4 April 2001 (04.04.2001) GB(71) Applicant (for all designated States except US): KIDDE  
PLC [GB/GB]; Mathisen Way, Colnbrook, Slough SL3  
0HB (GB).

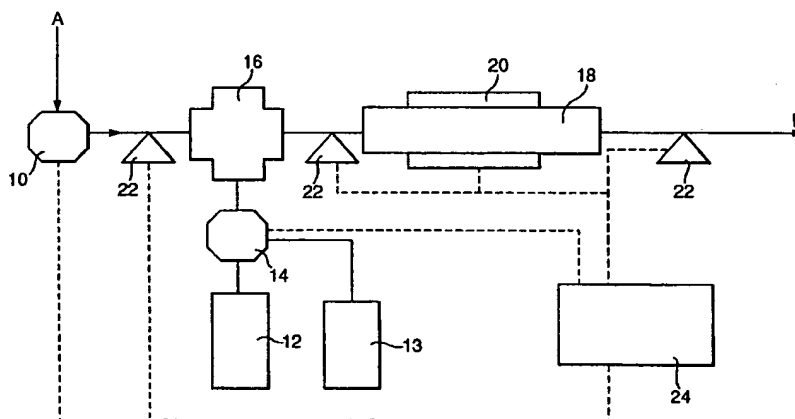
(72) Inventor; and

(75) Inventor/Applicant (for US only): SPRING, David, John  
[GB/GB]; 25 Springate Field, Langley, Slough, Berkshire  
SL3 7DH (GB).(74) Agent: MATHISEN & MACARA; The Coach House,  
6-8 Swakeleys Road, Ickenham, Uxbridge UB10 8BZ  
(GB).(81) Designated States (*national*): AE, AG, AL, AM, AT, AU,  
AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,  
CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH,  
GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC,  
LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW,  
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SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ,  
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Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),  
European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR,  
GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent  
(BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR,  
NE, SN, TD, TG).**Published:**

- with international search report
- before the expiration of the time limit for amending the  
claims and to be republished in the event of receipt of  
amendments

[Continued on next page]

(54) Title: FIRE PROTECTION SYSTEMS AND METHODS



(57) **Abstract:** Air from an air source A, which may be the bleed air of an aircraft, enters the system under the control of an air flow control unit (10). An organic fuel from a fuel reservoir (12 or 13) enters a mixing chamber (16) under the control of fuel flow control unit (14) for mixture with the air. At a first stage the organic fuel is a oxygenated organic fuel from reservoir (12), and at a subsequent stage the organic fuel is a hydrocarbon fuel from reservoir (13). The air and fuel mixture passes to a catalyst bed (18) containing a noble metal catalyst such as platinum, palladium or a mixture thereof. A relatively low temperature, non-flaming reaction occurs and the resultant gas mixture contains a low concentration of oxygen and larger qualities of inert gases such as nitrogen, carbon dioxide and water vapour. This post reaction mixture, which leaves the system at B, is suitable for suppressing and extinguishing fires, and is especially suitable for purging of air from cargo compartments on board aircraft during a flight on detection of a fire. A temperature control unit (20) associated with the catalyst bed (18) may be used to prevent its overheating during the reaction. A control unit (24) operates to control the air flow control unit (10), the fuel flow control unit (14) and the temperature control unit (20) in response to signals from sensing units (22) at various points in the system which detect various parameters such as the gas, pressure, temperature and flow.



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*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

## FIRE PROTECTION SYSTEMS AND METHODS

### Technical Field

The invention relates to fire protection systems and methods. Fire protection systems and methods according to the invention and to be described in more detail below, by way of example only, are particularly suitable for use in conditions where weight and size may present problems, such as on board aircraft or on other vehicles.

### Background Art

One method of suppressing or extinguishing a fire is to surround it with an inert atmosphere. This type of fire protection method is best suited to an enclosed space, where the air within is at least partly displaced by the inert atmosphere. The inert atmosphere could be produced using an inert gas or gases stored under pressure in cylinders, ready for deployment into the enclosed space when required. However, such cylinders are not appropriate where the weight and bulk of the fire protection system is to be minimised such as, for example, on board aircraft where space is limited and heavy components mean that less load can be carried.

GB-A-1395691 discloses an aircraft fuel tank inerting system comprising a catalytic reactor that reacts fuel and air, and a conduit for supplying the reaction gases to the fuel tank.

### Disclosure of the Invention

According to the invention, there is provided a fire or explosion protection system, comprising inert gas producing means operative to produce an inert gas output (B) using low temperature catalytic oxidation of organic fuel, and means operative to deploy the inert gas output into a region to be protected against the fire or explosion, wherein the inert gas producing means comprises mixing means operative to mix air (A) with the organic fuel and means operative to pass the resultant mixture over a noble metal catalyst, characterised in that the mixing means is operative in a first stage to mix the air (A) with organic fuel in the form of an oxygenated organic fuel and being operative in a second stage to mix the air (A) with organic fuel in the form of a hydrocarbon fuel whereby to produce the inert gas when the resultant mixture is passed over the heated catalyst.

According to the invention, there is further provided a method of protecting a region from fire or explosion, comprising the steps of mixing air from an air source (A) with organic fuel from an organic fuel source, passing the mixture over a catalyst for a low temperature oxidation reaction to produce an inert gas output (B), and passing the resultant inert gas output (B) into the region to be protected, characterised in that the mixing step comprises a first stage in which the fuel is an oxygenated organic fuel, and a second stage in which the fuel is a hydrocarbon.

### Brief Description of the Drawing

The accompanying drawing is a schematic block diagram of a fire protection system according to the invention. Fire protection systems and methods according to the invention such as for use on board aircraft will now be described, by way of example only, with reference to the accompanying drawing.

### Mode of Carrying out the Invention

The systems to be described generate inert gas in relatively large quantities and are of low weight and small size. They are therefore particularly suitable for use on board aircraft where weight and size are significant factors to be taken into account. However, they can be used in any other applications such as where low weight and small size are desirable, such as in other vehicles (military vehicles, for example).

In aircraft, the systems to be described are particularly suitable for suppressing or preventing fires or explosions in fuel tanks and cargo bays which present enclosed spaces (though not completely sealed), into which the inert atmosphere can be deployed.

In the case of aircraft fuel tanks, the size of the ullage space will clearly vary (increase) during flight, and the atmosphere within the ullage space will also vary during flight, changing its pressure and temperature as the aircraft climbs or descends. The atmosphere in the ullage space will also change its composition as decreases in the

ambient pressure cause dissolved gas in the liquid fuel to come out of solution, particularly oxygen which is more soluble in hydrocarbons than nitrogen. Therefore, the flammability of the atmosphere within the ullage space will vary during flight. For this reason, it is not practicable simply to fill the ullage space in the fuel tank with an inert atmosphere before take-off. It is therefore desirable to have on board the aircraft a system for producing inert gas during flight so that the desired quantity of inert gas can be fed into the tank ullage space according to the changing conditions there.

In the case of aircraft cargo bays, they are normally pressurised in substantially the same way as the aircraft passenger cabin, particularly because they are normally designed to carry livestock, and a flow of air is therefore arranged to enter the compartment throughout the flight. In the event of a fire in the cargo bay during flight, a fire extinguishant will be deployed into the cargo bay, such as Halon or a water spray. However, although this may extinguish the immediate fire, it may be impossible to prevent continual smouldering in the cargo bay because of the nature of the materials (passenger luggage in particular) which will be carried. Deployment of an inert atmosphere into the cargo bay is thus a very effective way of preventing or at least controlling such smouldering until the aircraft can reach a safe landing. Again, therefore, a means of generating an inert atmosphere on board the aircraft during flight is required.

The system shown in the Figure comprises an air flow control unit 10, a first fuel



reservoir 12, a second fuel reservoir 13, a fuel flow control unit 14, a mixing chamber 16, a catalyst bed 18 with an associated temperature control unit 20, sensor units 22, and a control unit 24.

Air enters the system from a source A at ambient or slightly elevated pressures, under the control of the air flow control unit 10. Fuel passes from either the first reservoir 12 or the second reservoir 13 under the control of the fuel flow control unit 14 into the mixing chamber 16 where it mixes with the air from the air flow control unit 10 (to be described in more detail below). The air and fuel mixture then passes from the mixing chamber 16 over the catalyst bed 18 for reaction with a catalyst (also to be described in more detail below). The resultant inert gas mixture passes out of the system at B whence it can be fed into the ullage space of an aircraft fuel tank or into an aircraft cargo bay.

Preferably, the fuel in the first reservoir 12 is an oxygenated organic material such as methanol,  $\text{CH}_3\text{OH}$ , or ethanol,  $\text{C}_2\text{H}_5\text{OH}$ , or a mixture thereof. Such fuels react on the catalyst without preheating of the catalyst bed 18. The fuel in the second reservoir 13 can be a gaseous or liquid hydrocarbon such as a heptane or gasoline or aviation kerosene. With such fuels it is necessary to preheat the catalyst bed 18 to  $400\text{-}500^\circ\text{C}$  to initiate a reaction.

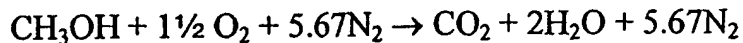
Initially oxygenated organic material as described is used from the first reservoir 12,

followed by a hydrocarbon fuel as described from the second reservoir 13, once the catalyst has been heated sufficiently through the reaction with the oxygenated organic fuel. The advantage of this approach is that hydrocarbon fuels remove more oxygen per unit mass than oxygenated organic fuels and are therefore more weight-efficient. This is, of course, an important consideration for a system for use on board an aircraft.

The hydrocarbon fuel is preferably supplied from the aircraft's primary fuel supply, i.e. the fuel supply for the aircraft engines. In this instance the second reservoir 13 would be the (or one of) the aircraft's conventional fuel tanks. This is advantageous because no additional tank for the hydrocarbon fuel for the system is required, reducing the overall weight of the system.

The fuel can be mixed with the air flow from the source A in the mixing chamber 16 by any suitable means, such as by passing the air through liquid fuel so as to saturate the air with fuel vapour, or by spraying liquid fuel under pressure into the air stream at such a temperature that it all evaporates; the fuel may be metered into the air stream under the control of the fuel flow control unit 14 by any convenient means such as an electric pump or under stored gas pressure. A convenient source of air A on board an aircraft is the bleed air of the aircraft. Its flow into the system is regulated by the air flow control unit 10. It will be appreciated that the source of air A could comprise any suitable source and is not limited to the bleed air of the aircraft.

The following oxidation reaction occurs on the catalyst bed 18 if methanol is the fuel:-



This results in a gas mixture of composition 11.5 vol % CO<sub>2</sub>, 65.4 vol% N<sub>2</sub> and 23.1 vol% H<sub>2</sub>O. Thus the oxygen in the air from source A is replaced with gases such as carbon dioxide and water vapour which do not support combustion and which, furthermore, result in an enhancement of the extinguishing performance of the mixture as compared with pure nitrogen. It is this gas mixture that is produced at the output B.

The system will produce inert gases as long as it has fuel and air. The methanol fuel is a liquid and preferably is stored in a pressurised storage container.

The catalyst on the catalyst bed 18 requires high thermal stability, mechanical strength and resistance to any poisons found in the fuel. It may be any metal from Group VIII of the Periodic Table, such as platinum, palladium, rhodium or iridium. These materials could alternatively be used in the form of their most active oxides. Preferably the catalyst comprises substantially platinum or palladium, or mixtures, since the reaction with the incoming air and fuel mixture from the mixing chamber 16 will start without preheating of the incoming mixture.

The catalyst may comprise fine metal particles (for example in the range 3-20nm) disposed on an inert mineral-based support. This type of support may comprise

alumina or aluminosilicates in fibrous or crystalline form, or porous granules or a honeycomb monolithic structure made from alumina, alumina/silica combinations or other inert oxides. The support is structured so as not to impede gas flow through the catalyst bed 18 but to maintain a sufficient contact time between the reactants (the incoming air and fuel mixture from the mixing chamber 16) and the catalytic surface.

The temperature control unit 20 may be necessary to prevent overheating of the catalyst bed 18 due to the heat generated by the reaction, because the efficiency of the catalyst may deteriorate with overheating. For example, the catalyst temperature should be kept below 1000°C to prevent sintering whereby the catalyst particles would fuse together.

The temperatures generated by the reaction are considerably less than those generated by flaming combustion, which are typically greater than 1500°C, because the reaction occurs at the catalyst surface and there is no flame. The temperature control unit 20 may also be used to preheat the catalyst bed 18 should this be necessary to start a reaction.

The system operates under the control of the control unit 24, which receives feedback from the sensor units 22, each of which can sense gas, pressure, temperature and flow. There is one sensor unit 22 located between the air flow control unit 10 and the mixing chamber 16, another located between the mixing chamber 16 and the catalyst bed 18, and a third located downstream of the catalyst bed 18. The control unit 24 operates to control the air flow control unit 10, the fuel flow control unit 14 and the temperature

control unit 20 in response to the feedback from the sensor units 22 to ensure that the system is working efficiently and safely and the gas concentrations leaving at B are within specified ranges. It is important that the fuel concentration in the air is kept on the lean side of stoichiometric, because if the mixture from the mixing chamber 16 becomes rich, the exhaust from the catalyst bed 18 at B will contain significant quantities of unreacted fuel and of carbon monoxide. The latter is especially undesirable because of the possibility of back leakage of gases from the cargo compartment into the passenger compartment.

The control unit 24 controls, by fuel flow control unit 14, from which of the first 12 and second 13 reservoirs fuel is supplied. The control unit 24 may switch the supply of fuel to the mixing chamber 16 from the first reservoir 12 to the second reservoir 13 when it receives an indication from temperature control unit 20 that the catalyst is sufficiently heated to allow a reaction to occur with the hydrocarbon fuel stored in the second reservoir 13.

Alternatively, the control means will switch the fuel supply from the first reservoir 12 to the second reservoir 13 when it receives an indication that only a predetermined quantity of fuel remains in the first reservoir 12. An indication to switch reservoirs is preferably given when the reservoir 12 is substantially empty. That the reservoir 12 is empty may be determined by a liquid level sensor, by a timer (indicating the period over which fluid has been supplied from the first reservoir 12) or a flow sensor (a

reduced flow rate indicating that the fuel is running out). It may be advantageous to empty the reservoir 12 because, firstly, the organic fuel has a relatively low flash point – so is, itself, hazardous to store, and, secondly, the weight burden of stored fuels would be reduced. With such an arrangement, the amount of stored organic fuel will preferably be just sufficient to heat the catalyst to the desired temperature.

It will be appreciated that the control unit 24 could also control the fire detection means and the fire protection system used to provide the initial knockdown of the fire.

The air and fuel need not be mixed in a mixing chamber. There may be more than three sensor units in the system; each sensor unit may sense different parameters.

In the case of aircraft fuel tanks, the inert gases produced at the output B may be deployed into the ullage space in controlled amounts during flight according to the changing conditions of pressure and temperature within the fuel tank and the fuel usage. This deployment can be automatic under control of suitable sensors. In this case, therefore, the deployment of the inert gases is purely for prevention purposes and does not rely on detection of a fire or explosion.

In the case of an aircraft cargo bay, deployment of the inert gases into the cargo bay will normally occur in response to detection of an actual fire by means of suitable fire detectors within the cargo bay. In response to the initial detection of the fire, a fire

knock down system will be activated for quickly suppressing the fire. This system may take any suitable form, such as using a rapid discharge of Halon or a Halon replacement agent or a water spray system. This will then be followed by deployment of the inert gases into the cargo bay, at the same time shutting off the normal air flow into the cargo bay. The inert gases will need to be supplied constantly in order to compensate for any leakage of air into the compartment or leakage of inert gas from the compartment.

In either case, the inert gases need not be generated at the region to be protected. The catalyst bed 18 of the invention may be located at a point remote from the region to be protected, the resultant inert gas mixture being passed through ducting to the region.

One suitable location for the catalyst bed 18 is in an auxiliary power unit (APU) compartment, because such compartments are usually located outside the fire wall and the pressure shell of the aircraft, and are themselves fire-protected. Locating the catalyst bed 18 remote from the region to be protected reduces the risk associated with having the fuel source 12 close to the region.

Although the systems described are particularly suitable, because of their low weight and small size, for fire protection purposes on board aircraft, they are not limited to such applications. They may be used in any other applications for fire or explosion purposes, particularly where low weight and/or small size are desired, such as on board other vehicles such as military vehicles, trucks or railway trains for example. Their low

weight and small size makes them advantageous over other methods of generating inert gas outputs, such as pyrotechnic inert gas generators and air separation techniques. The former are a very high density storage medium and are able to generate large amounts of inert gas very rapidly. However, the pyrotechnic nature of the reaction to generate the gas and the hot gases produced render this method unsuitable for many applications, particularly on board aircraft. The latter, including adsorptive gas separation such as pressure swing adsorption (PSA) over molecular sieves, selective permeation through polymer membranes, and cryogenic fractionation of liquid air involve the use of high pressures and complicated machinery, which is very heavy and therefore not desirable for use in many applications, again particularly on board aircraft.



CLAIMS

1. A fire or explosion protection system, comprising inert gas producing means operative to produce an inert gas output (B) using low temperature catalytic oxidation of organic fuel, and means operative to deploy the inert gas output into a region to be protected against the fire or explosion, wherein the inert gas producing means comprises mixing means (16) operative to mix air (A) with the organic fuel and means operative to pass the resultant mixture over a noble metal catalyst (18), characterised in that the mixing means (16) operative in a first stage to mix the air (A) with organic fuel in the form of an oxygenated organic fuel (12) and being operative in a second stage to mix the air (A) with organic fuel in the form of a hydrocarbon fuel (13) whereby to produce the inert gas when the resultant mixture is passed over the heated catalyst (18).
2. A fire or explosion protection system according to claim 1, wherein the oxygenated organic fuel and/or the hydrocarbon fuel is a liquid.
3. A fire or explosion protection system according to claim 1 or 2, wherein the oxygenated organic fuel (12) comprises methanol and/or ethanol.
4. A fire or explosion protection system according to claim 1, 2 or 3, wherein the hydrocarbon fuel (13) is kerosene.

5. A fire or explosion protection system according to any one of claims 1 to 4, including means (24) for rendering the mixing means (16) operative in the second stage when the catalyst (18) has reached a predetermined temperature.
6. A fire or explosion protection system according to any one of claims 1 to 4, including means (24) for rendering the mixing means (16) operative in the second stage, the means being responsive to an indication that a predetermined quantity of the oxygenated organic fuel is present in a reservoir thereof.
7. A fire or explosion protection system according to claim 6, wherein said predetermined quantity is selected to be indicative of the reservoir being empty.
8. A fire or explosion protection system according to any one of claims 1 to 7 wherein the catalyst (18) is from Group VIII of the Periodic Table.
9. A fire or explosion protection system according to claim 8, wherein the catalyst (18) is substantially platinum.
10. A fire or explosion protection system according to claim 8, wherein the catalyst (18) is substantially palladium.

11. A fire or explosion protection system according to claim 8, wherein the catalyst (18) is substantially a mixture of platinum or palladium.
12. A fire or explosion protection system according to any one of claims 1 to 11, wherein the catalyst (18) is contained in a catalyst bed.
13. A fire or explosion protection system according to any preceding claim, wherein the region is an enclosed space.
14. A fire or explosion protection system according to claim 13, wherein the region is on board an aircraft.
15. A fire or explosion protection system according to claim 14, wherein the enclosed space is the ullage space of a fuel tank.
16. A fire or explosion protection system according to claim 14, wherein the enclosed space is a cargo compartment.
17. A fire or explosion protection system according to any one of claims 14 to 16, wherein the air is the bleed air of the aircraft.
18. A fire or explosion protection system according to any one of claims 14 to 17,

wherein the hydrocarbon fuel (13) is provided from the aircraft primary fuel supply.

19. A fire or explosion protection system according to any preceding claim, wherein the inert gas producing means is located remote from the region to be protected.

20. A method of protecting a region from fire or explosion, comprising the steps of mixing air from an air source (A) with organic fuel from an organic fuel source, passing the mixture over a catalyst (18) for a low temperature oxidation reaction to produce an inert gas output (B), and passing the resultant inert gas output (B) into the region to be protected, characterised in that the mixing step comprises a first stage in which the fuel is an oxygenated organic fuel (12), and a second stage in which the fuel is a hydrocarbon (13).

21. A method of protecting a region from fire or explosion according to claim 20, wherein the oxygenated organic fuel and/or the hydrocarbon fuel is liquid.

22. A method of protecting a region from fire or explosion according to claim 20 or 21, wherein the fuel (12) in the first stage comprises methanol and/or ethanol.

23. A method of protecting a region from fire or explosion according to claim 20, 21 or 22, wherein the hydrocarbon fuel (13) is kerosene.

24. A method of protecting a region from fire or explosion according to any one of claims 20 to 23, wherein the second stage begins when the catalyst (18) has reached a specified temperature.
25. A method of protecting a region from fire or explosion according to any one of claims 20 to 24, wherein the second stage begins in response to an indication that a predetermined quantity of oxygenated organic fuel is present in a reservoir thereof.
26. A method of protecting a region from fire or explosion according to claim 25, wherein the predetermined quantity is selected to be indicative of the reservoir being empty.
27. A method of protecting a region from fire or explosion according to any one of claims 20 to 26, wherein the catalyst (18) is from Group VIII of the Periodic Table.
28. A method of protecting a region from fire or explosion according to claim 27, wherein the catalyst (18) is substantially platinum.
29. A method of protecting a region from fire or explosion according to claim 27, wherein the catalyst (18) is substantially palladium.
30. A method of protecting a region from fire or explosion according to claim 27,

wherein the catalyst (18) is substantially a mixture of platinum or palladium.

- 31 A method of protecting a region from fire or explosion according to any one of claims 20 to 30, wherein the catalyst (18) is contained in a catalyst bed.
32. A method of protecting a region from fire or explosion according to any one of claims 20 to 31, wherein the region is an enclosed space.
33. A method of protecting a region from fire or explosion according to claim 32, wherein the region is on board an aircraft.
34. A method of protecting a region from fire or explosion according to claim 33, wherein the enclosed space is the ullage space of a fuel tank.
35. A method of protecting a region from fire or explosion according to claim 33, wherein the enclosed space is a cargo compartment.
36. A method of protecting a region from fire or explosion according to claims 33 to 35, wherein the air source is the bleed air of the aircraft.
37. A method of protecting a region from fire or explosion according to any one of claims 33 to 36, wherein the hydrocarbon fuel is provided from the aircraft primary

fuel supply.

38. A method of protecting a region from fire or explosion according to any one of claims 20 to 36, including the steps of controlling the air source (A) by means of an air flow control unit (10), and controlling the fuel source by means of a fuel flow control unit (14).

39. A method of protecting a region from fire or explosion according to claim 38, wherein each of the air flow control unit (10) and the fuel flow control unit (14) is under the control of a control unit (24).

40. A method of protecting a region from fire or explosion according to any one of claims 20 to 39, including the step of controlling the temperature of the catalyst (18) by means of a temperature control unit (20).

41. A method of protecting a region from fire or explosion according to claim 40, wherein the temperature control unit (20) is under the control of a control unit (24).

42. A method of protecting a region from fire or explosion according to claim 41 when dependent on claim 31, wherein the control unit (24) also controls the air flow control unit (10) and the fuel flow control unit (14).

43. A method of protecting a region from fire or explosion according to any one of claims 38 to 42, further including the steps of sensing various parameters of the gases in the mixture including the gas, pressure, temperature and flow, at points prior to mixing, post mixing and post reaction, the air flow unit, the fuel flow unit and the temperature control unit operating in response to the detected parameters.

44. A method of protecting a region from fire or explosion according to any one of claims 20 to 43, including the step of knocking down the fire by another method prior to passing the generated inert gas mixture into the region to be protected.

45. A method of protecting a region from fire or explosion according to claim 44, wherein the knocking down step is controlled by the control unit (24) of claim 42.

46. A method of protecting a region from fire or explosion according to claim 42, wherein the step of detecting the fire is under the control of the control unit (24).





## INTERNATIONAL SEARCH REPORT

national Application No

PCT/GB 02/01531

## A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 A62C39/00 A62D1/06 A62C3/06

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 A62C A62D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 918 679 A (CRAMER FRANK B) 6 July 1999 (1999-07-06) the whole document ---	1-46
A	US 1 395 691 A (WARE WILLIAM P) 1 November 1921 (1921-11-01) cited in the application the whole document ---	1-46
A	US 6 095 251 A (MITCHELL ROBERT M ET AL) 1 August 2000 (2000-08-01) the whole document -----	1-46

☐

Further documents are listed in the continuation of box C.

☒

Patent family members are listed in annex.

## \* Special categories of cited documents :

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\*L\* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

\*O\* document referring to an oral disclosure, use, exhibition or other means

\*P\* document published prior to the international filing date but later than the priority date claimed

\*T\* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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Date of the actual completion of the international search

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European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
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# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/GB 02/01531

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 5918679	A	06-07-1999	FR 2785816 A1	19-05-2000
			JP 2000120500 A	25-04-2000
			DE 19847297 A1	15-04-1999
			GB 2330303 A ,B	21-04-1999
			US 6012533 A	11-01-2000
US 1395691	A	01-11-1921	NONE	
US 6095251	A	01-08-2000	US 6082464 A	04-07-2000
			AU 8498998 A	16-02-1999
			WO 9904860 A1	04-02-1999

## DETECTION OF EXPLOSIVE MIXTURES IN THE ULLAGE OF AIRCRAFT FUEL TANKS

Shin-Juh Chen<sup>1</sup> and Joel A. Silver<sup>2</sup>

Southwest Sciences, Inc.  
1570 Pacheco Street, Suite E-11  
Santa Fe, New Mexico 87505

Sensors for detecting explosive mixtures in the ullage of aircraft fuel tanks along with inerting systems are of paramount importance for preventing fires and explosions during ground and flight operations of both commercial and military aircraft. A diode laser-based oxygen sensing system is designed and tested to assess its ruggedness and performance in simulated flight conditions and fuel tank environment. This sensor system incorporates recent innovations in microelectronics such as digital signal processors, new vertical surface cavity lasers, high sensitivity absorption spectroscopy, and mechanisms for preventing liquid interferences on optical surfaces. Metal foams and sintered metals of different porosities were tested and found to prevent liquid interferences as a result of liquid sloshing/splashing and immersion without compromising the sensor's time response. Liquid droplets on optical surfaces can interfere with the sensor's performance. Gravity-driven flow on surfaces can remove most of the liquid. Kerosene fuel tends to form a thin liquid film on optical surfaces. The sensor's performance was not adversely affected by this thin film. However, coatings and motions encountered during flight could further enhance the removal of liquid off optical surfaces.

### INTRODUCTION

#### Motivation

The effective prevention and control of fires and explosions originating in fuel systems during in-flight, maintenance, and post-crash are critical for both commercial and military aircraft. From 1970 to 1993, thirteen military aircraft suffered total hull loss as a result of non-combat fuel tank explosions [1]. From 1959 to 2001, fourteen commercial aircraft have experienced fuel tank explosions [1] which resulted in 231 fatalities worldwide. As the liquid fuel is consumed, a space (also called ullage) containing air and fuel vapors is developed above the liquid fuel. This fuel-air mixture is potentially dangerous if an explosive composition, favorable environmental factors, and an ignition source are present. Methods to reduce the oxygen concentration in this fuel-air mixture are necessary for the survivability of both commercial and military aircraft. These methods displace the oxygen inside the ullage with

nitrogen. Moreover, monitoring systems are also needed to accurately determine the oxygen content inside the ullage and the quality of the inerting gas.

#### Onboard Inert Gas Generation System

Replacing the fuel vapor-laden space (ullage) inside the fuel tank as the liquid fuel is being consumed with Nitrogen-Enriched Air (NEA) minimizes fires and explosions due to potential ignition sources such as lightning strikes, artillery shells, static discharge, wiring sparks, and heating sources. Air separation technologies for the Air Separation Module (ASM) include pressure swing adsorption, hollow fiber membrane, ceramic membrane, cryogenic air separation, and hybrids [2]. The NEA contains usually more than 90 percent nitrogen. The ullage oxygen concentration should be between 9–12 percent to eliminate potential in-tank fires and explosions [2] due to all possible ignition sources.

An Onboard Inert Gas Generation System (OBIGGS) generally encompasses an ASM to generate NEA, a compressor, storage tanks, and a distribution system. The military has OBIGGS currently installed in the AH-64, C-5, C-17, F-22, and V-22 to reduce oxygen levels below the

1. AIAA Member; Senior Research Scientist
2. Principal Research Scientist

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lower explosive limit inside the fuel tanks. OBIGGS is currently being considered for commercial aircraft to reduce the likelihood of in-tank fires and explosions. Ground and flight tests are already underway to design effective inerting systems for the commercial aircraft [3–5].

### The Need for Oxygen Sensors

Oxygen sensors for monitoring the NEA exiting the Air Separation Module (ASM) of OBIGGS and inside the ullage are required to fully assess the effectiveness of inerting systems. Currently, there is no commercial oxygen sensor system that has been flight-certified to operate in the ullage of aircraft fuel tank. Zirconium oxide oxygen sensors are used to monitor the quality of the NEA at the ASM outlet for military aircraft. However, these sensors cannot be used in commercial aircraft since the sensor operates at high temperature and can be an ignition hazard.

Having the sensor inside the fuel tank provides the best and most direct approach to assess fire and explosion hazards. Existing technologies based on electrochemistry (e.g. zirconium oxide), fluorescence quenching, and paramagnetic properties of oxygen for measuring oxygen concentrations are not suitable for aircraft fuel tanks because the presence of fuel vapor in the ullage prevents safe sensor operation and inhibits optimal performance. Diode laser-based sensor systems may be the only viable solution for monitoring oxygen inside aircraft fuel tanks.

### Objective of this Research

This paper will focus on the design of a diode-laser based oxygen sensor system that is compatible with the aircraft fuel tank environment and flight conditions. This sensor system integrates recent technological advancements in microelectronics such as digital signal processors, new vertical cavity surface emitting lasers, high sensitivity absorption spectroscopy, and the development of innovative shields to prevent liquid interferences of optical surfaces. In particular, methods for minimizing the optical surfaces from getting wet during sloshing/splashing and immersion scenarios are investigated.

## METHODS

### Absorption Spectroscopy

The measurement of chemical species concentrations by

diode laser absorption, as depicted in Fig. 1, is based on straightforward implementation of Beer's law,

$$\frac{I}{I_0} = \exp(-\alpha), \quad \alpha = S(T)g(\nu)n\ell = \sigma(\nu)n\ell \quad (1)$$

where  $I_0$  is the light intensity incident on the gas sample,  $I$  is the transmitted intensity and  $\alpha$  the absorption coefficient. The absorption coefficient is comprised of the absorption line strength  $S(T)$ , the line shape function  $g(\nu)$ , number density  $n$  in  $\text{cm}^{-3}$  and path length  $\ell$  in cm. The line strength is a measure of how strongly light is absorbed and is a function of temperature but not pressure. The line shape function describes the wavelength dependence ( $\nu$ ) of the absorption and does depend on both temperature and pressure. The absorption cross section term  $\sigma(\nu)$  is the product of  $S(T)$  and  $g(\nu)$ , and has units of  $\text{cm}^2$ . For conditions of varying temperatures, the line shape function is best described by a Voigt profile [6].

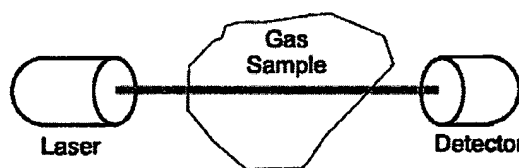


Figure 1. Optical absorption schematic

In the low absorbance limit ( $\alpha \ll 1$ ),

$$(I_0 - I) / I_0 = \alpha \quad (2)$$

and the fractional absorbance is linear in concentration and quantitative. This method is a line-of-sight technique, so that the absorbances are always spatial integrals along the optical path. Since the quantity actually measured is the ratio of  $I$  to  $I_0$ , the resulting concentration is independent of any laser intensity fluctuations and depends only on accurately-known parameters. The low absorbance limit is valid here.

### Wavelength Modulation Spectroscopy

High-sensitivity [7–10] is achieved by using wavelength modulation spectroscopy (WMS) to shift the detection band from DC (where laser amplitude noise can obscure weak absorbances) to high frequencies where laser excess ( $1/f$ ) noise is unimportant. Fractional absorption sensitivities

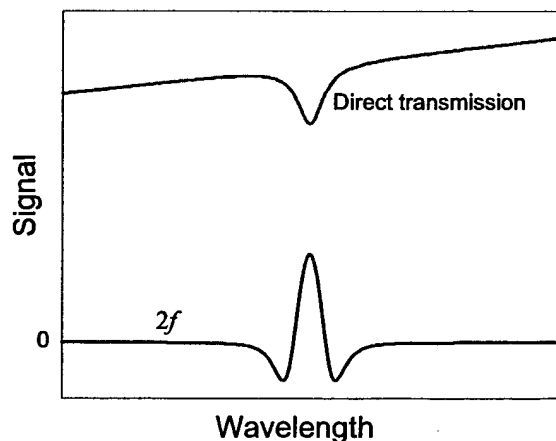
near the shot-noise limit ( $\sim 10^{-7}$ ) can be achieved [9]. Field measurements using WMS *routinely* maintain minimum detection absorbances of better than  $10^{-5}$  (at 1 Hz bandwidth) for extended (many month) operations [11–13]. For comparison, direct transmission methods such as FTIR are only capable of detecting  $10^{-3}$  absorbances.

To implement WMS, a small sinusoidal modulation at frequency  $f$  is superimposed on the diode laser injection current. This current modulation produces a modulation of the laser wavelength, since wavelength is tuned by changing the current. The amplitude of the current modulation is chosen so that the induced wavelength modulation is comparable to the width of the spectral feature under study. Absorption by the target gas converts the laser wavelength modulation to an amplitude modulation that induces ac components in the detector photo-current. Phase-sensitive electronics are then used to demodulate the detector photo-current at a selected harmonic,  $nf$  (typically,  $n = 2$ ). Studies have shown that detection frequencies as low as 20 kHz are often sufficient to bypass laser excess noise.

The WMS signal is directly proportional to the absorbance,

$$\text{Signal} = C I_0 \alpha(v) \quad (3)$$

where  $C$  is a system calibration factor and can be accurately predicted from known electronics factors and spectroscopic properties of the system. Since the cross section, path length and  $I_0$  are readily known or measured, the gas concentration is determined directly.

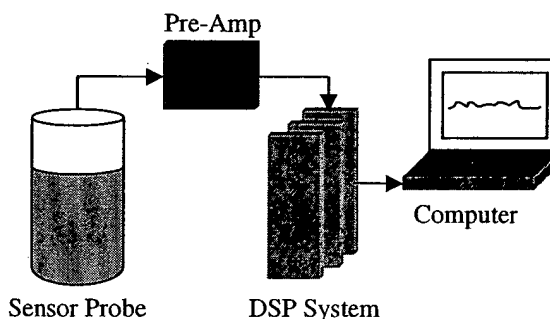


**Figure 2.** Direct transmission and corresponding  $2f$  signals.

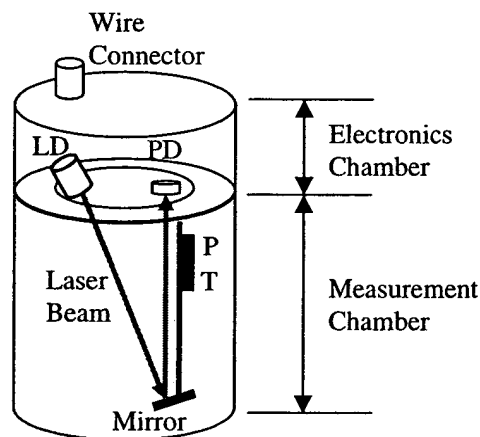
The signal from this detection method appears as approximately the second derivative of the absorption feature with respect to wavelength, as shown in Fig. 2. To first order, diode lasers have linear current versus intensity curves. Thus,  $2f$  signals have a zero background.

### Oxygen Sensor System

The oxygen sensor system is composed an *in situ* probe for measuring oxygen concentrations in the ullage of an aircraft fuel tank, a pre-amplifier board for signal processing, a DSP system for control, data acquisition and processing on-the-fly, and a computer for data visualization and storage. A schematic of the system is shown in Fig. 3.



**Figure 3.** Schematic of the oxygen sensor system showing the sensor probe with metal foam, pre-amp, DSP system and a computer.



**Figure 4.** Schematic of the sensor probe showing the electronics and measurement chambers. Laser diode (LD) and photodiode detector (PD) are in the electronics chamber. Pressure (P) and temperature (T) sensor, and mirror are in the measurement chamber.

The sensor probe is made of two chambers as shown in Fig. 4. The top chamber is about 3.5 inches long and 3.5 inches in diameter. This chamber houses a vertical cavity surface emitting laser which provides the light source for the wavelength modulation spectroscopy, and a silicon photodiode detector for collecting the transmitted intensity. On the bottom of this section a quartz window provides optical access into the lower chamber, while protecting the electronics from the ambient environment. A focusing lens is attached to the laser and the whole system sits on an optical mount which allows both coarse and fine positioning of the laser beam into the bottom chamber. This top chamber can be sealed from the environment and filled with an inert gas such as nitrogen during operation inside the aircraft fuel tank. A pressure sensor can be also installed inside to monitor the integrity of this sealed chamber.

The lower chamber is the measurement region where a mirror lies near the bottom to reflect the laser beam back into the top chamber onto the photodiode detector. The laser beam is reflected off the mirror surface only once to generate a total optical path length of about 20 cm. Pressure and temperature sensors are installed inside this chamber to monitor the ambient conditions and for quantifying the oxygen measurements. The optical surfaces inside this chamber needs to be protected from liquid splashing/sloshing and immersion without comprising the sensor's time response.

#### Vertical Cavity Lasers

A recent innovation in diode lasers is the development of vertical cavity surface emitting lasers (VCSEL). In contrast to conventional distributed feedback (DFB) single-mode lasers, which emit from the side of a complex semiconductor chip requiring many structural layers and fabrication steps, VCSELs emit upwards from the surface and as a result are easier to produce, can be tested during fabrication and can be more densely packed, thus lowering costs. Presently, these lasers are commercially available at wavelengths between 750 and 2050 nm [14]. Research is rapidly pushing the range of wavelengths towards both the UV (shorter wavelengths) and near-infrared (longer wavelengths).

VCSELs are extremely efficient and require only between 3 and 10 mA to operate. They can tune over 10-50  $\text{cm}^{-1}$  of wavelength, have collimated circular beams, and have output powers near 0.5 mW, which is more than sufficient for wavelength modulation spectroscopy. The low voltage

and low laser power make this VCSEL-based oxygen sensor system intrinsically safe. For comparison, conventional DFB lasers (generally available from 1000 to 2000 nm) require 10–20 times more power, have highly-diverging, astigmatic beams, and most importantly, only tune (*via* injection current) over about a single wavenumber. A consequence of the wide tunability of VCSELs is that selection of the optimal absorption line and/or detection of multiple gases is possible using a single laser. Size, optical and power requirements are significantly reduced as well. These VCSELs have been demonstrated to operate in environmental temperatures ranging from – 60 to 60 °C, and at pressures as low as 20 Torr [15].

#### Control and Data Acquisition and Processing

The DSP system is comprised of three piggy-backed 2" × 6" circuit boards – a laser controller board, the DSP board and an I/O board. The laser controller board is used to provide needed circuitry beyond the standard features of a generalized DSP system. It contains only the thermoelectric cooler (TEC) control for the laser operating temperature, line drivers/receivers for all I/O devices, inputs for flow and temperature health monitors, and a set of LEDs for diagnostic purposes.

The I/O board contains two high-speed (570 kHz, 18-bit) analog-to-digital (A/D) converters and four slower ones (200 kHz, 16-bit). It also has six digital-to-analog output converters (200 kHz, 16-bit). All of these are tied through a 100-pin interface connector to the laser controller board, using active line drivers and receivers to assure minimal noise and distortion. The high speed ADCs have a six-pole, 100 kHz anti-aliasing filter to assure that the WMS inputs are clean. Thirty-two digital I/O lines are also available. One D/A is used to generate the wavelength ramp and modulation waveform to each laser. The high speed A/D digitizes the WMS signal for subsequent analysis. The slower A/D's is used to read ambient temperature and pressure, and other required control or health monitoring parameters.

The DSP control board includes a Texas Instruments TMS320C6711 processor, an FPGA (flash programmable gate array), 16 MB of SDRAM for data storage and 2 MB of Flash ROM to store the program. The DSP processor stores and runs a C-based software program, which is written on a regular PC and tested using a JTAG interface to the DSP board. Once the program is fully debugged, it is compiled, linked and converted to a binary file which is

then burned into flash ROM memory on the DSP board.

In addition to this three board DSP package, an additional board is used. This small circuit board plugs into the electrical pins from the laser and photodiode, and from this board a shielded coaxial cable runs to the main electronics unit. This circuit board contains a pre-amplifier for the photodiode, a photoconductive bias circuit (to permit larger input signals while maintaining better linearity), connections to housing and ambient temperature sensors, and the VCSEL laser current driver. This last device is mounted as close to the laser as possible because of the very low electrical currents used to drive this laser.

This system operates using a wall plug 6V transformer or four-AA 1.5V batteries. Output communications provided are an RS-232 (or RS-488) serial communications port, with optional capabilities (requiring straightforward

modifications) for a USB port, or (wireless) modem. The entire DSP/control package is extremely compact. It weighs about 6 ounces, has an overall size of  $6\frac{1}{4}'' \times 2\frac{1}{2}'' \times 1\frac{1}{2}''$ , and uses only a few Watts of electrical power.

Upon powering the system, the DSP board automatically loads and executes the program. The laser is brought to the set point temperature, then turned on and data acquisition begins. Multiple high speed spectral scans are co-averaged and the WMS data are demodulated, normalized, and fit to theoretical reference spectra to determine the local concentration of gas. The results of these fits, fitting statistics, and sensor health parameters are reported out via the communications port once per second (or as frequently as desired). The system could also be modified to use separate reference gases for analysis.

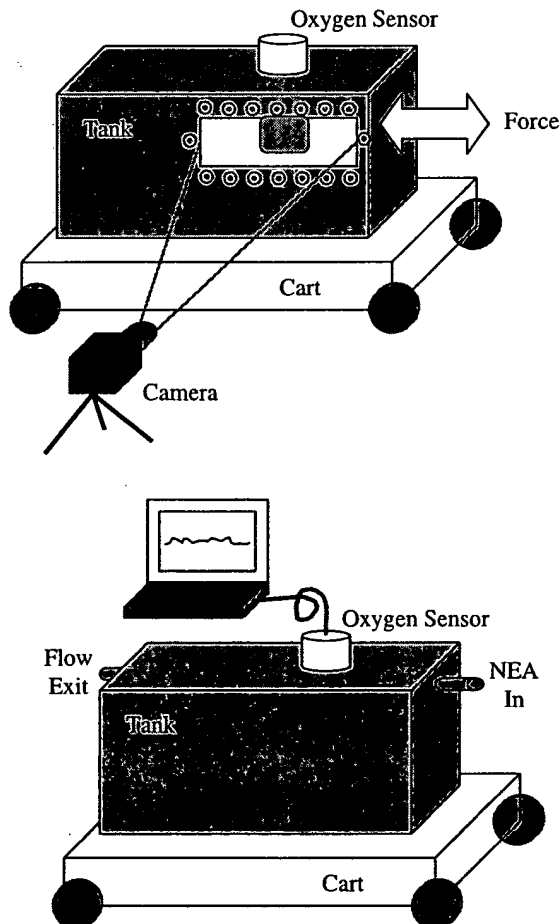
#### Simulated Liquid Sloshing/Splashing and Immersion

A 27 gallon rectangular plastic container was modified for the liquid sloshing/splashing tests (see Fig. 5). The tank is 12.5 inches wide, 30.75 inches long, 19.75 inches high, and has a wall thickness of 0.25 inch. A rectangular section of 18 inches wide and 5 inches high is cut out in one side and replaced by a transparent plexiglass for camera access. A 4.35 inch diameter hole is made on the top of the tank for mounting the sensor probe which extends about 5 inches into the interior of the tank. Metal foams of different porosities are used to assess their efficacy in minimizing or preventing the wetting of optical surfaces in the event of liquid sloshing and splashing. The tank is set on a four-wheel cart and sliding motions are applied to generate waves inside the tank for simulating in-tank sloshing and splashing.

Sintered metal discs of different porosities (6 to 35 micron average pore size) are mounted to one end of a cylindrical hollow tube with the other end closed. The discs are 2 inches in diameter and with thicknesses ranging from 1/16 to 1/4 inch. The end having the disc is immersed in liquid (water or kerosene) for several hours and monitored for leakage of liquid into the cylinder. These sintered metals are useful for designing a measurement chamber that is impermeable to liquids but allow gases to pass through the chamber.

#### Simulated Fuel Tank Inerting

A second rectangular plastic container is used for simulating fuel tank inerting (see Fig. 5). The sensor probe



**Figure 5.** Schematic of the simulated fuel tank for sloshing/splashing tests (*upper*) and inerting tests (*lower*).



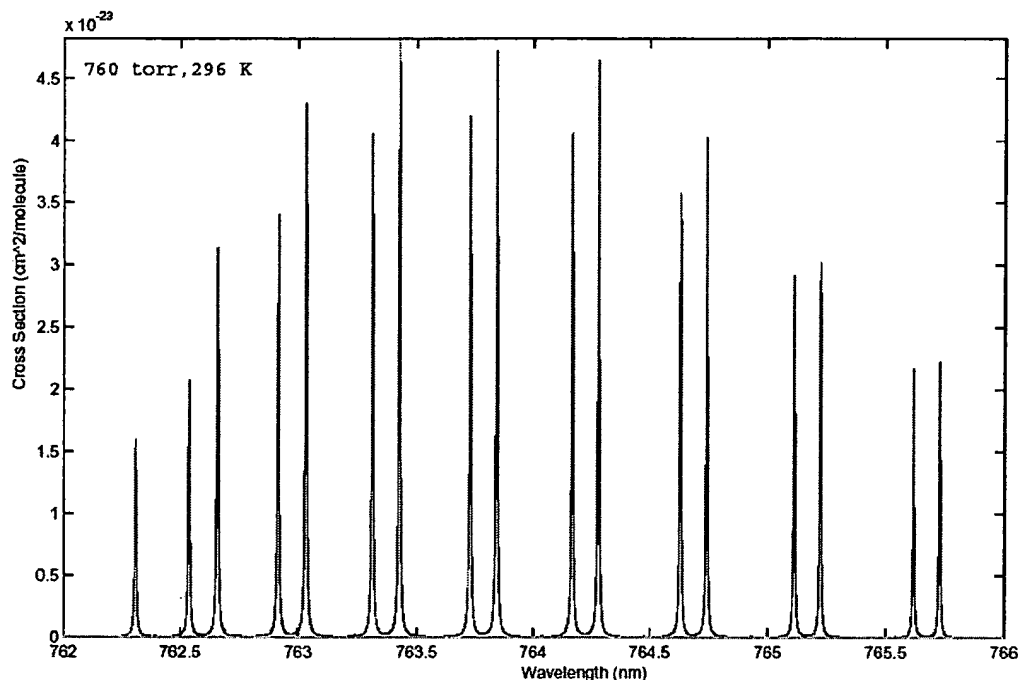


Figure 6. Oxygen absorption spectrum.

is mounted into the center top section of the tank. Two 3/8 inch holes are drilled on opposite ends near the top of the tank for the inflow of Nitrogen-Enriched Air (NEA) and outflow of gas. A certified mixture of 5% oxygen and 95% nitrogen is fed into the tank at a flow rate of 0.1 gal/sec. Flow rate is metered using a flow metering valve attached to a flow controller and computer. The effect of metal foams and sintered metals on the time response of the sensor system is determined.

#### Simulated Wetting of Optical Surfaces

A hand pump is used to generate droplets of water and kerosene. Liquid droplets are sprayed unto the reflecting mirror located in the lower chamber of the sensor probe, and the sensor's response to the liquid droplets is monitored. The liquid sprays range from fine (1/4 mm diameter) and dispersed spray to the flooding of the optical surfaces. The experiments were all conducted in ambient air and provided insight on additional mechanisms needed to remove liquid off optical surfaces.

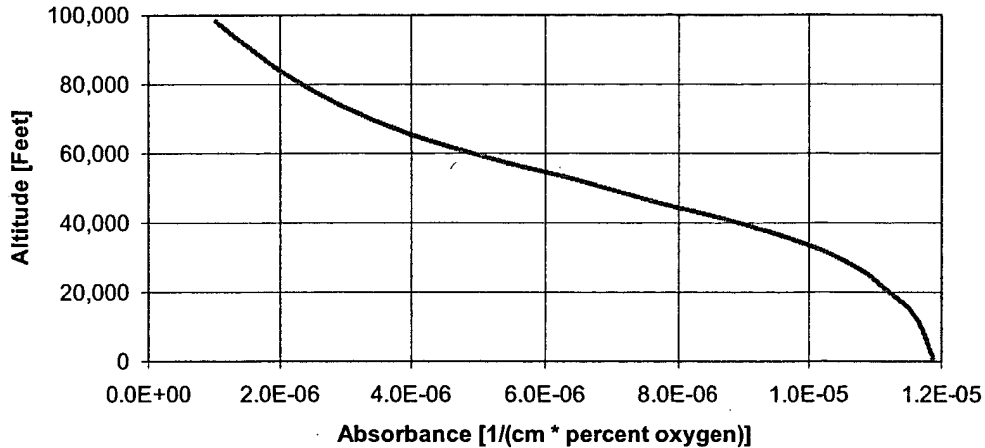
## RESULTS AND DISCUSSION

#### Sensitivity and Accuracy of Sensor System

Using HITRAN [16], Fig. 6 shows the oxygen absorption band in the 762 – 766 nm spectral region which has well resolved lines. This spectral region is generally inactive and is free of interference from other ambient and fuel species. One important advantage of an optical detection approach is that fuel vapor does not introduce background absorbance signals. This occurs for two reasons. First, hydrocarbons do not have significant absorption bands in the near-visible spectral region (~ 760 nm). Second, the very weak bands that do occur are spectrally broad and diffuse, whereas the WMS methods are sensitive only to sharp spectral features such as the lines in Fig. 6.

The effects of altitude (using Standard Atmosphere) on the sensitivity of the laser-based system is shown in Fig. 7. As altitude increases, the absorbance per total optical path length (in cm) and oxygen concentrations (in percent) is decreased. From equation 1, the absorbance is linearly proportional to the total optical path length and the number density. At 35,000 feet, using a total optical path length of 100 cm, 10 percent oxygen gives an absorbance of 0.01 with an achievable accuracy of  $\pm 0.1$  percent. Clearly, for most of the commercial aircraft, the change in altitude will have a minimal effect on the sensitivity and accuracy of a diode laser-based oxygen sensor system.

The ambient oxygen concentration was monitored over

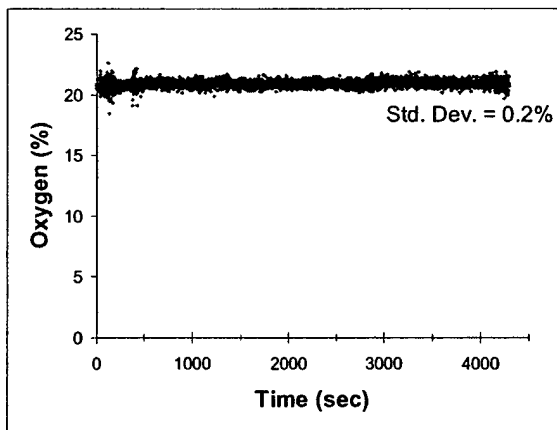


**Figure 7.** Effects of altitude on the sensitivity of the diode laser-based oxygen sensor system using Standard Atmosphere.

4300 seconds to determine the stability of the system. A standard deviation of 0.2 percent was found for the sensor system. Figure 8 shows a plot of the ambient oxygen concentration over the monitoring period. Averaging over one minute gives a standard deviation of about 0.3 percent. Note that the total optical path length was only 20 cm. Certainly increasing the total optical path length will increase the precision of the measurements. A Herriott cell [17] can be used to generate very large optical path lengths (order of meters) with a very short and low-volume measurement chamber.

#### Slosh/Splashing Guard

During a typical operation of an aircraft, unsteady motions (due to air turbulence, sudden acceleration and de-



**Figure 8.** Stability of oxygen sensor system at ambient conditions. Each dot represents data at each second.

acceleration) can modify the structure of the liquid layer inside the fuel tank. Even if the sensor probe was flush with top wall of the fuel tank, scenarios of liquid splashing onto the sensor probe is still possible. The liquid layer can move back and forth, filling up certain sections of the tank while emptying others. Sloshing motions with various amplitude and frequency can develop. Preventing the optical surfaces from getting wet is important to minimize the degradation of the sensor's performance. However, any preventive measure must not considerably increase the time response of the sensor to the changes in oxygen concentration inside the fuel tank (such as during inerting).

A metal foam shaped like a tall cup is used to enclose the lower chamber of the sensor probe. A metal bracket holds the cup to the upper chamber. The cup is highly porous and is 5 inches tall, 3.25 inches in diameter and 0.25 inches thick. The reflecting mirror for the optical path is located off-center near the bottom of the cup. The rectangular tank designed for liquid tests is half-filled with water and secured to a four-wheel cart. The tank is rocked back and forth to generate sloshing patterns, and the measurement chamber was splashed several times. Liquid easily drains off the metal foam. After a few sloshing tests, the sensor probe is removed from the tank, and the metal foam is removed to reveal the reflecting mirror. In all sloshing tests, the mirror never got wet. As water splashes onto the metal foam, the metal foam absorbs the impact energy. The liquid droplets do not penetrate the cup's wall to reach the interior. The liquid fills the pores inside the metal foam, and drains off quickly at the bottom of the cup. Preventing the wetting of optical surfaces due to sloshing/splashing can

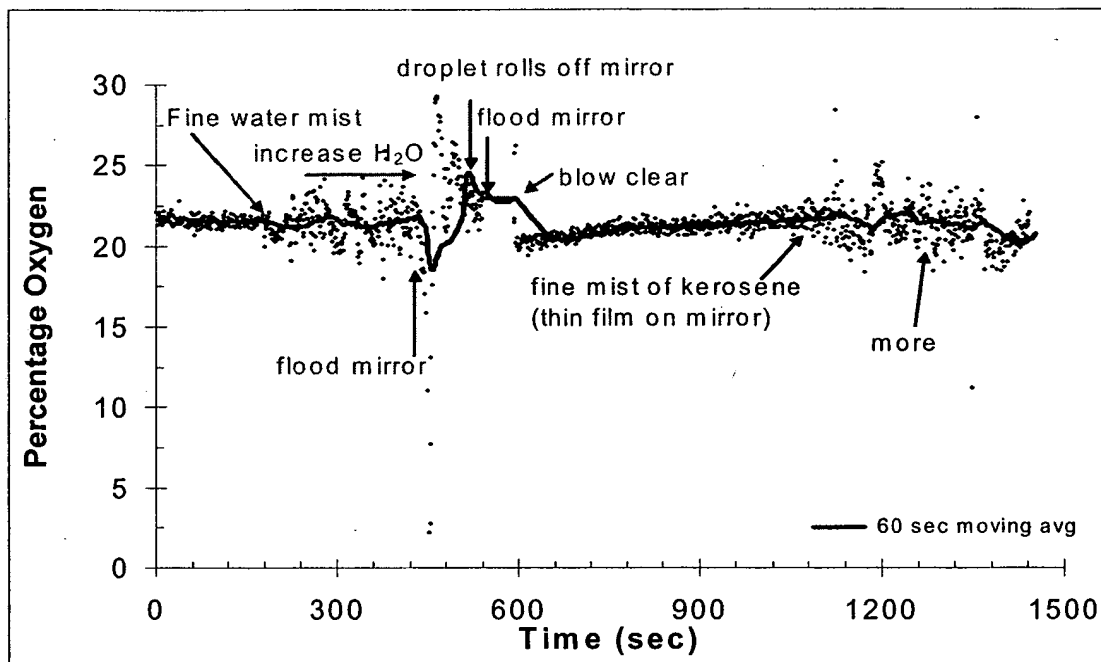


Figure 9. Water and kerosene droplets on optical surfaces and their effects on the sensor's performance.

be accomplished using a metal foam design which encloses the measurement chamber while allowing the chamber to breathe.

#### Liquid Immersion of Sintered Metal Discs

Sintered metals discs with average pore size ranging from 6 to 35 microns were immersed in liquids (water and kerosene) to assess their impermeability to liquids. In all cases of liquid immersion (up to several hours), liquid was not found inside the testing chamber. Selection of the appropriate pore size depends on the required sensor's time response to changes in oxygen concentrations and the disc's impermeability to liquid.

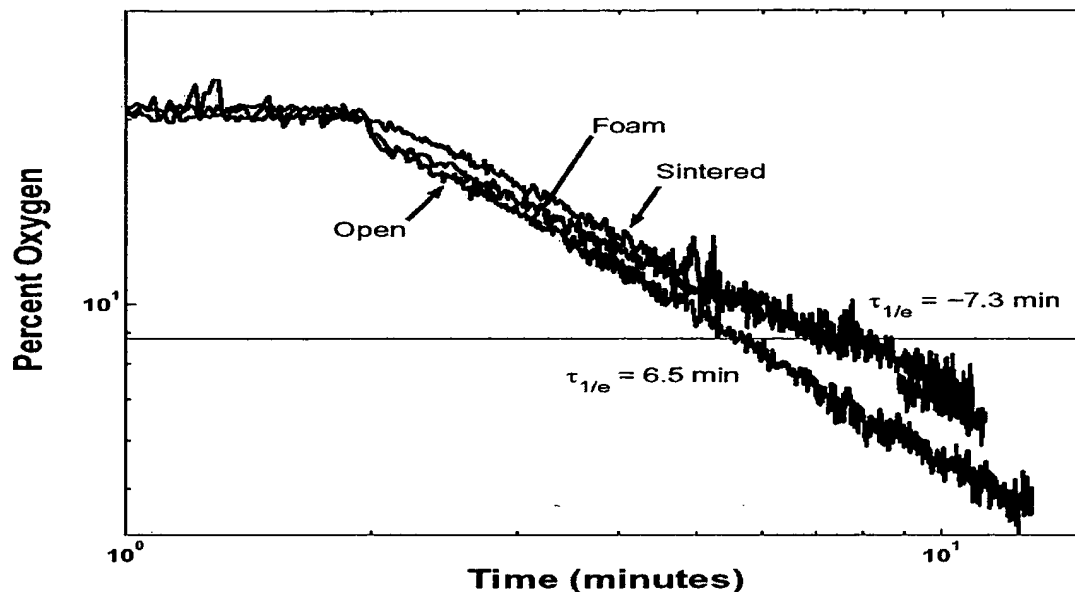
#### Wetting of Optical Surfaces

The reflecting mirror inside the measurement chamber is angled about 15 degrees from the horizontal. This was necessary to redirect the incoming laser beam onto a photodiode detector located inside the upper chamber. Any liquid deposited on the surface will initially runoff due to gravity and leave a thin liquid film due to surface tension. The competition between surface tension and gravity will affect how fast the liquid film runs off the surface. Sprays of water and kerosene were deposited on the mirror surface, and the sensor's performance was monitored.

Figure 9 shows the sensor's response to various sprays of water and kerosene. Fine water droplets ( $< 1/4$  mm) on the mirror surface do not degrade the sensor's performance as seen in times between 150 and 450 seconds. Although the data collected appeared scattered, the 60-second moving average shows a reasonable performance. Since water droplets will bead on the mirror surface, the increase in water droplets lead to the formation of larger droplets via coalescence as the droplets roll down the surface due to gravity. Once the droplet diameter is larger than the laser beam diameter (about  $1/2$  mm), the laser beam can no longer reflect off the mirror surface and reach the photodiode detector. This can be seen in times between 450 and 600 seconds in Fig. 9. Blowing the surface to remove the water droplets recovers the sensor's normal operation.

As for the kerosene droplets, the increase from a fine spray to the point of flooding does not lead to the loss of laser signals. The kerosene droplets do not bead on the mirror, but forms a thin liquid film. Although the one second data looked scattered, the 60-second moving average still shows a reasonable concentration of oxygen.

The vibrations and accelerations encountered during normal flight conditions can further enhance the removal of liquid droplets or liquid film off the optical surface. Obviously, a



**Figure 10.** Time response of sensor system with the measurement chamber open, surrounded by a metal foam cup, and closed with a metal tube having a sintered metal disc at the bottom.

coating that is compatible with the fuel environment can further improve the removal of liquid off optical surfaces.

#### Simulated Fuel Tank Inerting

Using the 27 gallon rectangular tank designed for the inerting tests, the lower chamber of the sensor probe was subjected to three test conditions to estimate the relative diffusion rates of air into the chamber. These are (1) open chamber, (2) chamber surrounded by a metal foam, and (3) a metal tube with a sintered metal installed at the bottom. Oxygen concentrations were recorded each second. For each test condition, the tank started with an ambient oxygen concentration. NEA is fed to the tank at a flow rate of 0.1 gallon per second.

Figure 10 shows the oxygen concentration as a function of time for the three test conditions. Data were collected until the oxygen concentration inside the tank is below 8 percent. To reach a  $1/e$  concentration (i.e 7.7 percent  $O_2$ ), it took 6 minutes for the open chamber to reach this level. However, it took only one additional minute for the metal foam and sintered metal test conditions to reach  $1/e$  oxygen point. As expected, the sensor probe with a metal foam has a time response between that of a sensor with an open chamber and sintered metal disc. The results suggest that using a metal foam and sintered metal to minimize the wetting of optical surfaces due to sloshing/splashing and immersion

scenarios do not considerably increase the time response of the sensor system. A time response of one minute should be sufficient for monitoring oxygen concentration in the ullage and quality of NEA at the ASM outlet. Under real operating conditions, the aircraft motion of the liquid should reduce the mixing times. For oxygen measurements below 10 percent, a longer total optical path length would be required to reduce the noise seen in Fig. 10.

#### SUMMARY AND CONCLUSIONS

To prevent fires and explosions originating from aircraft fuel tanks, the ullage must be inerted using nitrogen-enriched air. Oxygen sensors are needed to monitor the ullage and quality of nitrogen-enriched air. A diode laser-based oxygen sensor system was determined to be a feasible sensor for probing the ullage of aircraft fuel tanks. The laser-based system is immune to fuel vapors and environmental conditions encountered during flight.

For a laser-based system to be successful, the optical surfaces must be kept free of liquid droplets. Gravity-driven flow on optical surfaces can remove most of the liquid. A thin liquid film is typically formed when kerosene fuel contact the optical surfaces. Such thin liquid film did not adversely affect the performance of the sensor system. Mirror coatings and motions encountered in flight can

further aid in the removal of liquid off the optical surfaces.

Mechanisms for preventing or minimizing the entry of liquid into the measurement chamber can include metal foams and sintered metal parts. These mechanisms were shown to provide sufficient protection from liquid sloshing/splashing and immersion without sacrificing the sensor's time response.

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### REFERENCES

1. Federal Register, Department of Transportation, Fuel Tank Ignition Prevention Measures, Vol. 62, No. 64, Thursday, April 3, 1997.
2. Reynolds, T. L., Eklund, T. I. and Haack, G. A., Onboard Inert Gas Generation System/Onboard Oxygen Gas Generation System (OBIGGS/OBOGS) Study, Part II: Gas Separation Technology – State of the Art, NASA CR-2001-210950 (2001).
3. Burns, M. and Cavage, W. M., Inerting a Vented Aircraft Fuel Tank Test Article with Nitrogen-Enriched Air, DOT/FAA/AR-01/6 (2001).
4. Burns, M. and Cavage, W. M., Ground and Flight Testing of a Boeing 737 Center Wing Fuel Tank Inerted with Nitrogen-Enriched Air, DOT/FAA/AR-01/63 (2001).
5. Burns, M. and Cavage, W. M., A Description and Analysis of the FAA Onboard Oxygen Analysis System, DOT/FAA/AR-TN03/52 (2003).
6. Hui, A. K. Armstrong, B. H., and Wray, A. A., Rapid Computation of the Voigt and Complex Error Functions, *J. Quant. Spectrosc. Radiat. Transfer* **19**, 509-516 (1978).
7. Silver, J. A., Frequency Modulation Spectroscopy for Trace Species Detection: Theory and Comparison Among Experimental Methods, *J Appl. Opt.* **31**, 707-717 (1992).
8. Silver, J. A. and Stanton, A. C., Two-Tone Optical Heterodyne Spectroscopy Using Buried Double Heterostructure Lead-Salt Diode Lasers, *Appl. Opt.* **27**, 4438 (1988).
9. Bomse, D. S., Stanton, A. C., and Silver, J. A., Frequency Modulation Spectroscopy For Trace Species Detection: Experimental Comparison of Methods, *Appl. Opt.* **31**, 718-731 (1992).
10. Bomse, D. S., Dual-Modulation Laser Line-Locking Scheme, *Appl. Opt.* **30**, 2922 (1991).
11. Stanton, A. C., Silver, J. A., Bomse, D. S., Oh, D. B., Hovde, D. C., Paige, M. E., and Kane, D. J., Applications of Diode Laser Spectroscopy to Environmental and Industrial Process Monitoring, in *Application of Tunable Diode and Other Infrared Sources for Atmospheric Studies and Industrial Process Monitoring*, A. Fried, ed., *Proc. SPIE* **2834**, 41 (1996).
12. Silver, J. A. and Hovde, D. C., "Near-Infrared Diode Laser Airborne Hygrometer," *Rev. Sci. Instrum.* **65**, 1691-1694 (1994).
13. Hovde, D. C., Meyers, T. P., Stanton, A. C. and Matt, D. R., "Methane Emissions from a Landfill Measured by Eddy Correlation Using a Fast Response Diode Laser Sensor," *J. Atmos. Chem.* **20**, 141 (1995).
14. Vertilas, [www.vertilas.com](http://www.vertilas.com)
15. Paige, M. E., Diode Laser Water Vapor Sensor for Weather Balloons, R02-01, Southwest Sciences Internal Report (2001).
16. L.S. Rothman, R.R. Gamache, et al., *J. Quant. Spectrosc. Radiat. Transfer* **48**:469 (2001).
17. D. Herriott, H. Kogelnik and R. Kompfner, "Off-Axis Paths in Spherical Mirror Interferometers," *Appl. Opt.* **3**, 523-526 (1964).